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# Large-scale photovoltaic systems in airports areas: safety concerns

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ABSTRACT

The development of large-scale Photovoltaic energy-production systems is one of the promising solutions to replace fuel-based and nuclear-based electricity plants. Compared to most sources of electricity, photovoltaic panels produce few $CO_2$ in operation (although their manufacturing, transport, installation, cleaning and decommissioning/recycling creates $CO_2$ emissions), they need little maintenance, last 20 years or more and can be recycled.

One of the key questions raised in developing large-scale PV systems is to find appropriate locations: flat, secured against vandalism and thieves, and near to existing power lines.

Airports areas fit quite well those constraints so an increasing number of airport authorities is installing or planning to install large surfaces of PV panels producing 20 MW or more.

In this paper, we address the safety concerns related to the implementation of large-scale PV systems in airport locations. We identify different kinds of risky situations in which PV panels are implied and we analyze their causes and potential consequences, along with proposals for risk reduction.



**Contents**



## 1. Introduction

The interest for solar energy is growing rapidly over the world (Fig. 1). In Europe, 21.9 GW were connected in 2011, compared to 13.4 GW in 2010; Europe still accounts for the predominant share of the global PV market, with 75% of all new capacity in 2011. China was the top non-European PV market in 2011, with 2.2 GW installed, and followed by USA with 1.9 GW. The number of markets achieving more than 1 GW of additional PV capacity during 2011 rose from three to six: Italy, Germany, France, China, Japan, USA [1].

≪ Solar photovoltaic (PV) electricity continued its remarkable growth trend in 2011, even in the midst of a financial and

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economic crisis and even as the PV industry was enduring a period of consolidation. As they have for the past decade, PV markets again grew faster than anyone had expected both in Europe and around the world. ≫ [1], p 5

In October 2010, already 15 US airports were operating solar facilities and the interest of airport authorities is growing rapidly. Airport sponsors are interested in solar energy for many reasons. Solar technology has matured and is now a reliable way to reduce airport operating costs. Among the environmental benefits are cleaner air and fewer greenhouse gases that contribute to climate change. [2]. Compared to other electric supply technologies
(Fig. 2), solar PV is among the lowest GHG producing ones [3].

While offering benefits in economical and environmental aspects, installation of large PV-covered areas in airports locations raise a number of concerns in terms of safety.

Among the first kinds of threats that have been studied, reflectivity of panels and interferences with navigation aids were given a special attention by authorities [2], as they have a direct potential effect on air traffic in the vicinity of airports and especially on landing, one of the most critical phases of flights.

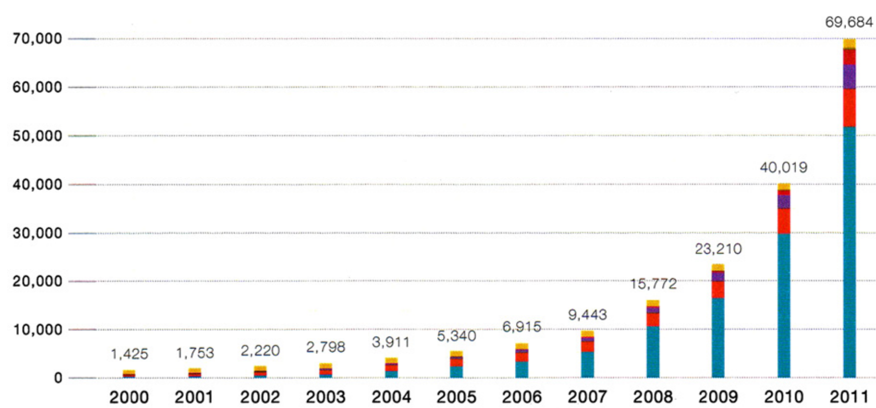
### 1.1. PV systems-related risks

Reflectivity of panels and its potential effect on pilots depends on two main factors: the reflectivity of the PV panel surface and the relative position of the panel surface with the daily and seasonal movement of the sun (sun chart) and with the trajectory of planes during landing, taxiing and take-off, for each runway of the airport.

In order to maximize energy transmission, PV panels are low-reflective devices (2% on the average). The possibility that reflected sun light crosses the path of airplanes can be computed [4] to assess the glare risk in terms of intensity and duration.

Moskowitz et al. [5], Fthenakis [6,7], and Caceres et al. [8] address the social impacts of PV technology and show that most of these impacts are related to the manufacturing phase (use of hazardous and toxic materials). In the use/operation phase, they only identify potential human damage from the leaching of materials from broken PV modules (Cadmium and Selenium) and fumes in case of accidental fires.

Turney and Ftnenakis [9] address the environmental impacts from the installation and operation of large-scale PV power plants. From a review of literature and experts' opinions, they identify 32 impacts of which 22 are beneficial, 4 are neutral, 5 are




| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROW | 751 | 807 | 887 | 964 | 993 | 1,003 | 1,108 | 1,150 | 1,226 | 1,306 | 1,209 | 1,717 |
| MEA | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | 21 | 205 | 336 |
| China | 19 | 30 | 45 | 55 | 64 | 68 | 80 | 100 | 145 | 373 | 893 | 3,093 |
| America | 146 | 177 | 222 | 287 | 379 | 496 | 645 | 856 | 1,205 | 1,744 | 2,820 | 5,053 |
| APAC | 355 | 491 | 677 | 902 | 1,178 | 1,475 | 1,797 | 2,080 | 2,643 | 3,409 | 5,116 | 7,769 |
| Europe | 154 | 248 | 389 | 590 | 1,297 | 2,299 | 3,285 | 5,257 | 10,554 | 16,357 | 29,777 | 51,716 |
| **Total** | **1,425** | **1,753** | **2,220** | **2,798** | **3,911** | **5,340** | **6,915** | **9,443** | **15,772** | **23,210** | **40,019** | **69,684** |

**Fig. 1.** Evolution of global cumulative installed capacity 2000–2011 (MW) [1].

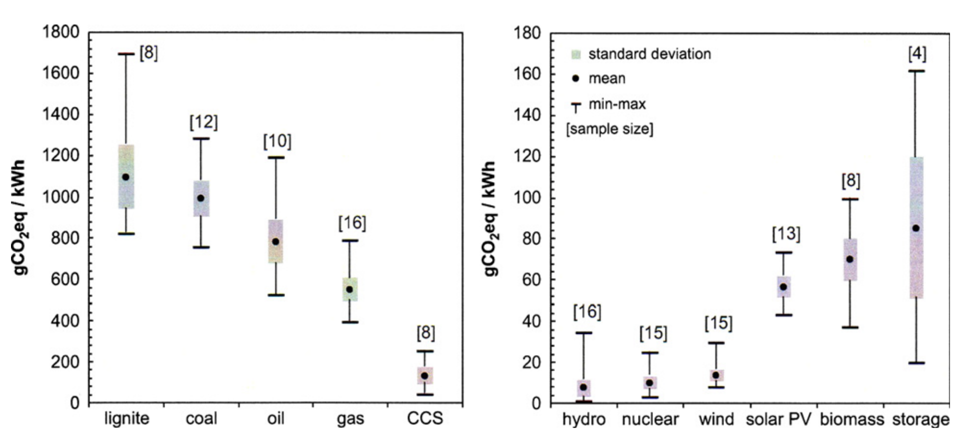



**Fig. 2.** life-cycle greenhouse gas (GHG) emissions from electric supply technologies [3].

unknown and only one is detrimental: flight hazards for birds (transmission lines).

Hernandez et al. [10] study the risks associated with the electrical connection of PV systems to the distribution networks and the protections needed for safe operation. By safe operation they mean safe for the PV system and safe for the network. Protections must be activated in the occurrence of failure scenarios: short circuits, overloads, high/low voltage, and frequency (p. 88).

Moskowitz et al. [11] address the risk of electrical shock and fire for people manipulating rooftop PV devices. They quote the 6 factors influencing the severity of shock hazard: type of circuit (AC or DC), voltage, impedance of the human body, current flowing through tissues, current pathway and contact duration (P. 328). By combining electrical properties of different sizes of PV systems with the effects of electric current on humans, they suggest (P. 332) that ventricular fibrillation and possible death may occur with only six PV modules connected in series (125 V, 250 mA through body) although PV systems are considered to be low voltage systems. Concerning fire risk, they estimate the risk not being a significant concern with a probability level of $10^{-6}$.

Moskowitz et al. [11] suggest using fault-tree analysis to identify failure modes and establishing an event and injury registry to assist designers in developing optimal prevention strategies (P. 335).

Levins [12] proposes a standard addressing different hazard situations: personal injury from electric shock, electric and thermal burns, parts that may cause lacerations and ignition of materials. PV systems, like batteries are devices where voltages are always present (P. 327). He argues that PV modules need to be capable of enduring harsh outdoor environments without degradation that might result in a hazard (P. 329). Levins [12] also addresses other parts of the safety system: grounding and grounding-fault protection, bypass and blocking diodes. He also suggests in-circuit arc detectors, as a PV device is a current generator, which means creating a strong arc current on opening circuit, but he concludes that he founded no solution for that.

### 1.2. Airport-related hazards

Modern civil airports merge very different activities, including air and ground traffic control, logistics, commercial business in consumers' areas and hotels, passengers, crews and public management, security checks, fuel management, aircrafts maintenance, customs, etc. In this paper, we focus on the safety of flight-related activities: airport approaches, takeoffs and landings.

Regulatory bodies like IACO[1] and FAA[2] define "object free" and "controlled activity" areas around runways in which it is forbidden to place obstacles not needed for air traffic, but outside those areas, those regulations do not set limits for installing ground-level devices as solar panels. [13]

A large number of air accidents occur during takeoff and landing phases. Kirkland et al. [13] study the main causes of accidents: crew technique and decision-related, flight crew performance-related, weather-related, and systems-related factors (P.22). Fig. 3 shows the number of runway excursions on landing for each type of factor.

Wong et al. [15,16] analyze a large set of data from airport normal operations and accidents to propose models for the four main types of accidents: landing overrun and undershoot, takeoff overrun and crash after takeoff. In the second part of duo-fold paper, they refine their analysis by examining the different accident scenarios, the trajectories and final location of planes.

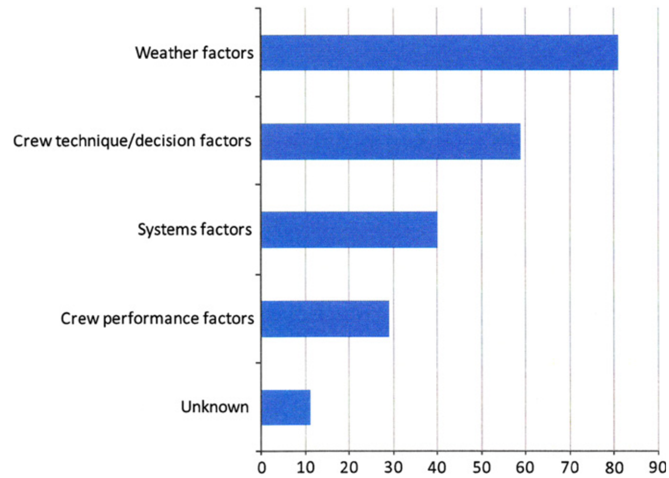



**Fig. 3.** Factors involved in runway excursions on landing [14].

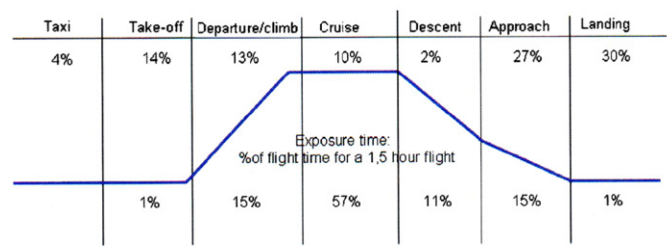



**Fig. 4.** Accidents percentage per phase of flight [17].

Then they compare the final wreckage sites with the Airport Safety Areas (ASA) defined by FAA authorities. In the case of landing overrun, they identify a clear discontinuity approximately 300 ft from the runway centerline, which is the FAA strip width requirement for Code 4[3] runways (P. 916).

More generally, Wong et al. [15,16] propose to set the safe distance taking in account a Target Level of Safety of $10^{-7}$ accident/movement. They argue that:

> "The proposed risk assessment methodology allows the length and width of ASAs to be tailored according to the residual risk at individual runways, such that the margin of safety provided meets the Target Level of Safety." [16]

In order to mitigate risks, authorities need to define safety areas next to the runway. Arnaldo-Valdes et al. [17] develop probabilistic models to estimate risks for using in the design of those safety areas. Their methodology includes 3 steps: collection of historical data, development of a model and formalization of the model in a database (P. 633). Based on historical values, Arnaldo-Valdes et al. [17] estimate the average frequency of accident per movement to 3,64 $10^{-7}$ (P. 646). Fig. 4 shows the relative part of the different phases of flight in the accident rate.

In a recent paper, Ayres et al. [18] summarize their work on location and consequence model, by accounting for more data and introducing the modeling of a new category of accident: veer-off crashes. Veer-off corresponds to a plane going out of the runway on the side, while in overrun and undershoot crashes, the wreckage location is almost aligned with the runway. Landing

[1] International Civil Aviation Organization.
[2] Federal Aviation Administration (USA).
[3] Code 4 corresponds to 1,800 m and over runway length.

veer-off accounts 40% of accidents; takeoff veer-off accounts for 8%.

Ayres et al. [18] provide a set of probability/distance models for the different kinds of accidents, based on a large database of accidents (260,000) collected from 11 countries. Compared with their former studies [14,15], these models cover longitudinal and transverse locations and address the consequences of planes striking obstacles.

Another source of risk for airplanes is the presence of wildlife in airports and especially birds. Birds entering in collision with planes may cause damage to pilots' windscreens and to reactors, causing their explosion. Blackwell et al. [19] analyze this problem and raise a number of concerns in terms of land-use. They identify three main land-use practices that contribute to wildlife hazards: stormwater management, land covers and natural areas (P. 4).

In order to address these different kinds of risks, aviation authorities have designed rules to prevent accidents and damage to planes, public and airports facilities. For instance, the European Aviation Safety Agency [20] defines rules for wildlife management, limitation of obstacles and projection of debris in the airspace, hazardous lights, protection of communications, prevention of fire and access limitations to the movement area.

Among the many recommendations, EASA addresses the question of frangibility[4] of equipments located in the vicinity of runways, in order to limit the consequences of a shock with a plane.

## 2. Methodology

Our objective is to assess the different risks related to large-scale PV systems located in airports areas. Our methodology uses focus groups; it is divided in three steps: identifying the main hazards and their potential causes and consequences, formalizing the scenarios and proposing measures to reduce the risks to an acceptable level by means of a bow tie approach [21–24].

Identification of the main hazards was done primarily by a literature review (see above) to get familiar with the different scientific domains and then by organizing a series of focus groups [25–27] to address the different kinds of hazards.

Each focus group was composed of a rather small number of specialists (5 to 7), representing the different groups of stakeholders: PV designers, electronics designers, mechanical experts, industrial safety experts, pilots and aviation authority.

Focus group sessions lasted 3 to 5 hours and were followed by reports sent to participants for the validation of conclusions. The diagrams (bow-ties) presented in this paper were built and discussed during the focus group sessions.

The first focus group was dedicated to electrical properties of PV systems. From an analysis of standard large-scale PV systems and taking in account existing hazard reduction measures, the focus group identified two sources of hazard relevant for installations located in airport fields: electric arc when opening a circuit and high DC voltage in the wiring.

The second focus group was dedicated to airport activities; it included pilots, representatives from the French aviation authority (DGAC) and an expert on wildlife hazard in airports. From the description of safety regulations and planes movements on and around airports and a review of past accidents, three sources of hazards were indentified. The first is wildlife hazard and especially bird nesting that can be facilitated by the presence of many PV panels. The second is the presence of debris on the runway resulting of interventions on the PV system or breakage of PV elements. The third one is the electric hazard for maintenance staff. The last one is reflection of sunlight by the PV panels that may create a glare risk for pilots.

The third focus group was dedicated to emergency interventions; it included firefighters, pilots and representatives from the French aviation authority (DGAC). From the analysis of past crashes in airports and rescue intervention methods, two main hazards were identified in case of accidental penetration of a plane in a large-scale PV system. The first is the damage caused by the structure supporting the PV panels to the airplane, including debris entering reactors or piercing kerosene tanks and causing fire. The second is the effect on passengers and crew evacuation and rescue teams' intervention.

The last focus group was dedicated to find technical and organizational measures to suppress or reduce the hazards identified by the other focus groups and to reduce the related risks to an acceptable value. It included PV systems designers, project managers, and electric systems developers.

The last step of the study was to describe and discuss the proposed risk-reduction measures with representatives from the French aviation authority.

In order to facilitate discussions during these four focus groups and formalization of accidents' scenarios, we used the bow tie method proposed by Chevreau et al. [28]. This method consists in using a simplified bow tie (generally no more than 2 levels of causes and consequences) as a facilitating artifact for a group to reach a consensus when assessing the level of risk of a given accident's scenario.

For each risky situation identified by the focus group, a bow tie is gradually drawn and discussed in the group, to set up, complete or modify the combination of potential causes and consequences. Once the bow tie is agreed by the group, participants are asked to evaluate probabilities of causes and severity of consequences, using a $5\times5$ scale proposed by European aviation authorities (Fig. 5).

During the last focus group, bow ties designed by the three first focus groups were used to determine the risk level without any reduction measures, using a conventional large-scale PV systems similar to those installed in country sites. Then the group identified which measures (preventive or protective) should be proposed to set risks at the same level than without the PV system and how to implement these measures. The objective being that residual risk is equal to the risk level without the PV

| | 1: Not significant | 2: Minor | 3: Major | 4: Hazardous | 5: Catastrophic |
|---|---|---|---|---|---|
| 5: Frequent | A | I | U | U | U |
| 4: Reasonably probable | A | I | U | U | U |
| 3: Remote | A | A | I | U | U |
| 2: Extremely remote | A | A | A | I | U |
| 1: Extremely improbable | A | A | A | A | I |

A: Acceptable
I: Improvable
U: Unacceptable

**Fig. 5.** Risk assessment matrix [20].

[4] Frangibility is the capacity of a device to break in known locations when a given energy is applied on it.

system, that is to say that the PV system does not increase the risk level.

## 3. Results

From the results of the focus groups, we have identified a series of six major accident scenarios corresponding to an unacceptable level of risk and which need preventive and protective measures. These major scenarios are:

- Wildlife hazard due to birds nesting in the PV system;
- Electric shock hazard during maintenance of the PV system;
- Debris of the PV system on the runway;
- Fire of a plane entering the PV system;
- Difficulties for evacuation in the PV system;
- Difficulties for rescue intervention in the PV system.

### 3.1. Wildlife hazard

Wildlife hazard in airports is mainly due to the presence of birds that fly around the areas where planes are flying low. There are different species of birds that may create a hazard: large clouds of small birds (starlings), big migratory birds, sea birds and more common birds that nest in areas where there are rest places and food, mostly insects. The potential consequences of birds colliding with planes are damage to the plane engines, governs and windscreen (Fig. 6).

The focus group has assessed the risk: probability 4, severity 4 (risk level: unacceptable) so measures must be taken. The group proposed 3 preventive measures that reduce probability to 2 (risk level: improvable):

1. set up a regular grass mowing below and around the PV system;
2. equip panels and structures with repulsive devices;
3. frighten away birds (this measure is already applied on all major airports).

### 3.2. Debris of PV panels on the runway

The risky situation corresponds to the presence of debris on the runway (Foreign Object Detected: FOD). These debris may come from the rupture of elements of the PV system: panels, wiring and structure. Several causes have been founded: strong wind, maintenance activities and shock with vehicles (Fig. 7).

Such debris on the runway caused some severe accidents, one the most dramatic being the crash of the Concorde (Paris, July 25th, 2000) that caused 113 fatalities.

By combining causes' probabilities (level 3) with consequences' severity (level 5), the risk level is unacceptable. A series of six preventive measures were proposed that allow reducing the probability to 1 (risk level: improvable):

1. Inserting a resistant weft in the PV panel to ensure its integrity;
2. Linking PV panels to the structure by steel wires to prevent panels flying;

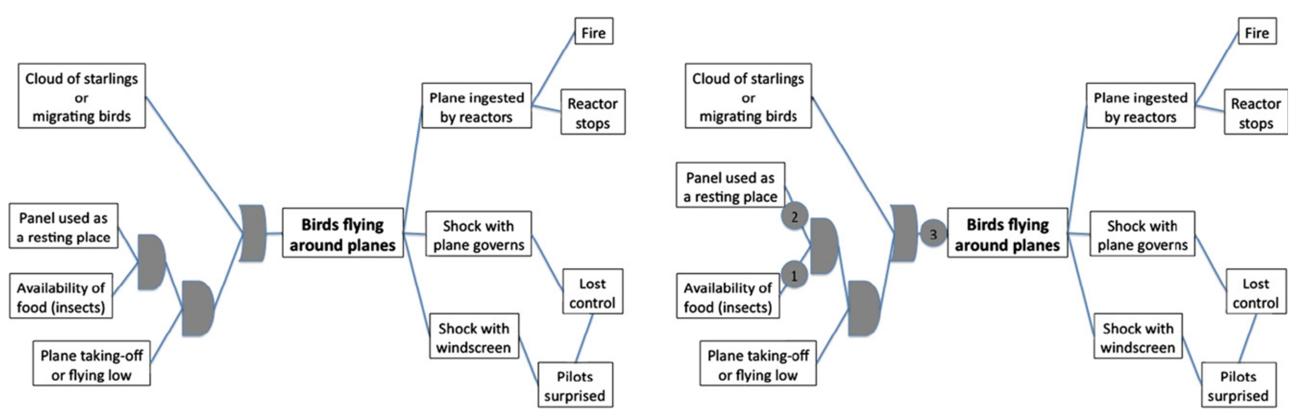



**Fig. 6.** Bow ties representing the risky situation "birds hazard" and proposed measures.

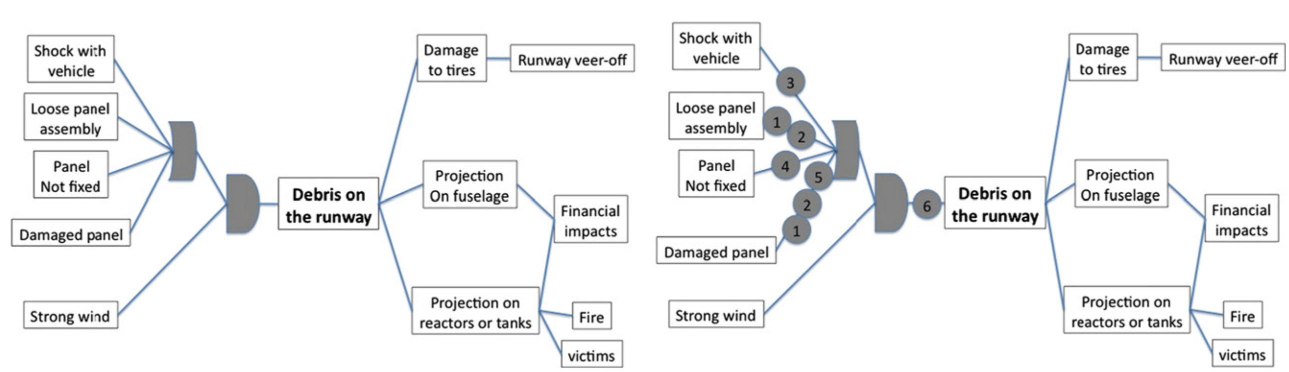



**Fig. 7.** Bow ties representing the risky situation "electric hazard" and proposed measures.

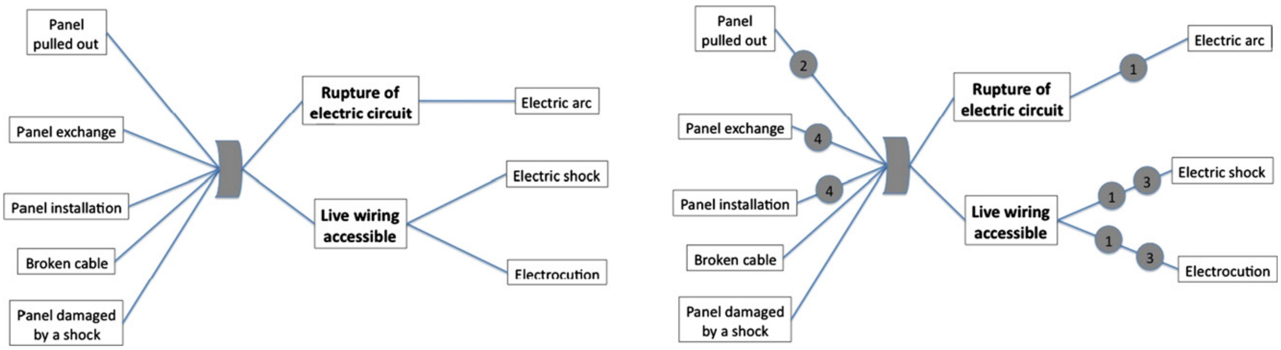



**Fig. 8.** Bow ties representing the risky situation "electric hazard" and proposed measures.

3. Setting up strict regulations and safe distances between the systems and circulation areas, in order to avoid shocks between vehicles and the PV system;
4. Avoiding non-fixed elements during installation and maintenance operations;
5. Regular checking of systems' integrity, especially after strong winds and maintenance interventions;
6. Checking for debris on the runway to prevent planes running on debris and tires damage. This preventive barrier already exists in all airports with a frequency depending on traffic level; it should be reinforced after episodes of strong winds and interventions on the PV system.

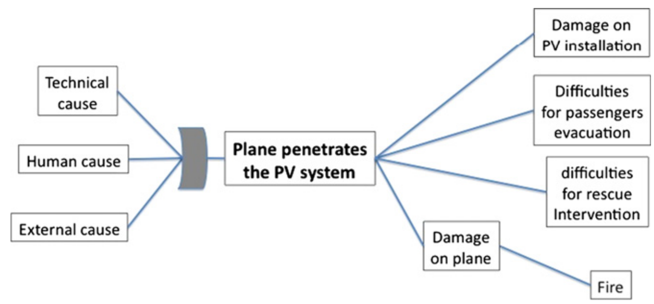



**Fig. 9.** Bow tie representing the risky situation "plane penetrating the PV system".

### 3.3. *Electric shock hazard*

PV panels are live components as soon as they are exposed to light. They behave as current generators, which means that breaking the circuit creates sparks and electric arcs. When PV panels are grouped in a large-scale system, they are linked to a series of electric components for DC/AC conversion and injection in the high voltage energy network. PV systems for airports are designed to minimize accessibility of high voltage lines and components by putting them in the earth. So the only external elements are the panels and the wiring connecting panels together and with conversion devices. Electric hazards corresponds to two possible scenarios: live elements or wires are accessible and may cause injury or death; rupture of a circuit may cause an electric arc that in turn may start a fire in presence of flammable liquids, gas or solids.

Without reduction measures, the risk level is unacceptable: probability=3; severity=4. Four measures were proposed by the focus group: 2 preventive and 2 protective:

1. Stop energy production when a PV panel is disconnected (intern electronic device);
2. Connect the PV panel to the structure by a steel cable to prevent pulling it out;
3. Avoid direct contact with live components by using insulating gloves;
4. Cover PV panels with a lightproof film when disconnected.

With these measures, risk level drops to acceptable with probability=2; severity=3 (Fig 8).

### 3.4. *Plane penetrating a large-scale PV system*

Although the two risky situations presented above are serious, the four focus groups agreed that the most dramatic scenario is a commercial plane entering a large-scale PV system after veering off the runway. We do not take in account the probability of a plane reaching the PV system (that will be located out of the Airport Safety Areas defined by aviation authorities), as the objective of this study is to find ways not to increase existing risks levels in airports. So we consider the situation in which a plane exits from the airport safety area and we examine if the presence of the PV system increases the risk level or not.

Fig. 9 resumes the generic bow tie for that scenario. The focus groups identified 3 scenarios covering the three major potential consequences: plane in fire; difficulties in the evacuation and difficulties in the rescue intervention.

#### 3.4.1. *Plane in fire*

There are two ways in which a fire may start when a plane enters in a large-scale PV structure: debris entering reactors and making them burn or explode, and torn structure piercing the fuel tanks in presence of electric arcs and sparks. Fig. 10 presents the bow ties associated to this scenario.

The risk level of this scenario is unacceptable: probability=4; severity=5. The focus group has identified 5 preventive measures:

1. Inserting a resistant weft in the PV panel to ensure its integrity;
2. Linking PV panels to the structure by steel wires to prevent panels flying;
3. using a frangible structure that breaks easily at precise locations;
4. Stopping energy production when PV panel is disconnected (by means of an internal electronic device that short-circuits the panel);
5. Avoid apparent wiring that can be pulled off.

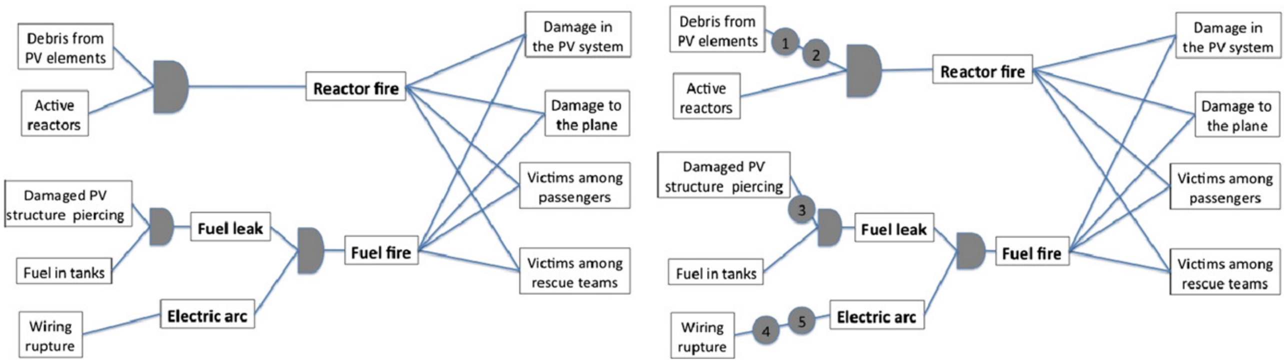



**Fig. 10.** bow ties corresponding to the risky situation "plane in fire".

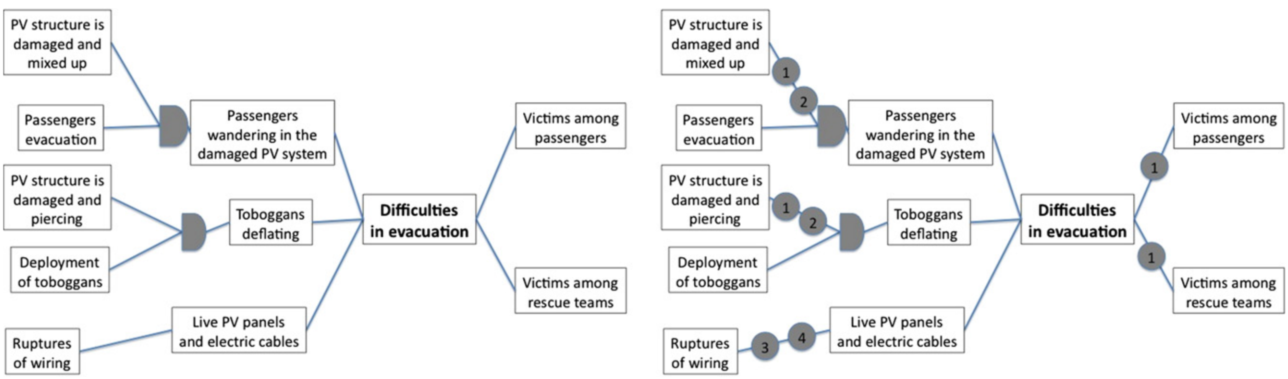



**Fig. 11.** bow ties corresponding to the risky situation "difficulties in evacuation".

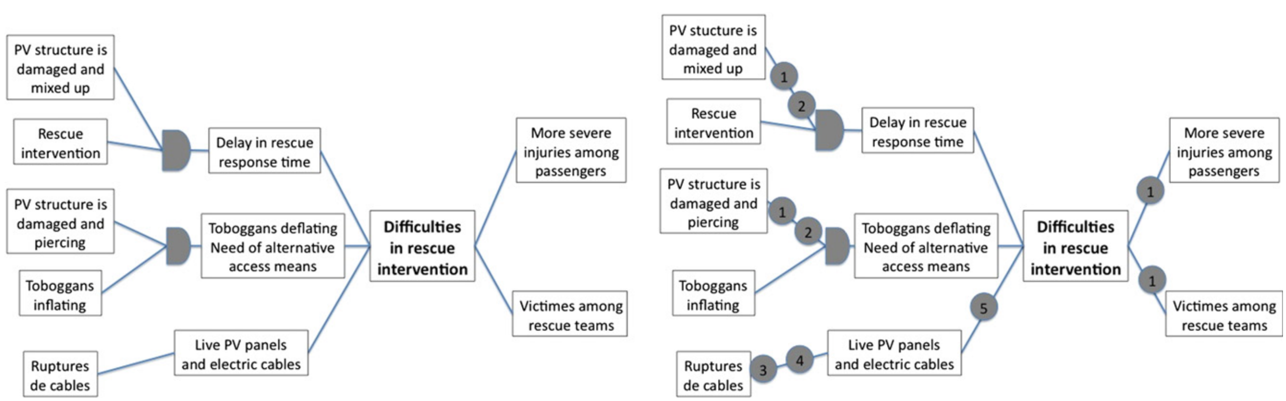



**Fig. 12.** bow ties corresponding to the risky situation "difficulties in rescue intervention".

The effect of these measures is to reduce the probability to 2, which makes the risk level improvable.

### 3.4.2. *Difficulties in evacuation*

Once the plane stops inside the PV system after veering off the runway, top priority is to evacuate passengers and crew, using emergency toboggans. First par of the scenario is the influence of the PV system torn structure on toboggans, which are inflatable structures. Piercing elements of structure may damage toboggans and prevent their use for evacuation.

The second part of the scenario is the circulation of passengers and crew in the damaged structure, which may slow down evacuation, cause falls and injuries. Moreover, presence of live electric cables and elements may also cause injuries (Fig. 11).

The focus group assessed the probability level to 4 and the severity level to 4, which corresponds to an unacceptable level of risk. 4 measures were proposed, one of them (No. 1) being preventive and protective:

1. Using individual supports for each PV panel and planning alleys in the PV system to facilitate circulation. This measure also contributes to reducing the severity of injuries.
2. Designing a frangible structure, especially the link between each panel and its structure, to make it foldable in case of shock and limit salient and sharp elements.

3. Stopping energy production when PV panel is disconnected (by means of an intern electronic device that short-circuits the panel);
4. avoid apparent wiring by inserting electric cables in the structure and placing DC/AC converters in the ground.

By combining these measures, probability is reduced to 2 and severity to 4, making the risk level improvable.

#### 3.4.3. Difficulties in rescue intervention

Intervention of rescue teams on a plane veering-off the runway needs a quick response and appropriate means and resources. National and international regulations define the conditions of such interventions and especially the delay to reach the spot of the crash. If a plane ends up its move in a large-scale PV system, the rescue intervention scenario can be divided in three steps. 1/ arrive on the spot in the middle of the PV system; 2/ set up evacuation means if the toboggans are not available; 3/ prevent contact with live electric wires and elements.

The focus group evaluated the probability of that scenario to 4 and its severity to 4, which results in an unacceptable risk assessment level. Five measures were proposed:

1. Using individual supports for each PV panel and planning alleys in the PV system to facilitate circulation. This measure also contributes to reducing the severity of injuries.
2. Designing a frangible structure, especially the link between each panel and its structure, to make it foldable in case of shock and limit salient and sharp elements.
3. Stopping energy production when PV panel is disconnected (by means of an intern electronic device that short-circuits the panel);
4. avoiding apparent wiring by inserting electric cables in the structure and placing DC/AC converters in the ground.
5. wearing individual protection equipments (IPE) to protect rescue teams against live electric elements and sharp debris.

The effect of these measures it to reduce probability to 2 and severity to 3, reducing the risk level to acceptable (Fig. 12).

## 4. Discussion

In this study, we have identified the influence on safety of large-scale PV systems installed in airports areas. Our main finding is that using conventional panels and support structures would result in aggravating the level of risks for all the major scenarios presented above and especially the scenarios related to a plane veering-off the runway and ending up its route in the system.

By using a bow tie representation of risk scenarios as an artifact facilitating the discussion among the different stakeholders, it was possible to describe the major scenarios in terms of combination of causes and consequences and to reach a consensus in each focus group.

Moreover, as the five focus groups used that methodology, it was possible to share the knowledge and to identify what kinds of measures could be proposed to reduce those risks at the same level than without the PV system.

We noted that some of these risk scenarios correspond to risk levels “improvable” when assessed by the stakeholders. This corresponds to the fact that even with the best prevention and protection measures, accidents in aviation are still possible, especially veer-off crashes on landing and the potential severity still remains important as it can be observed on the international statistics of accidents [13,18,14]. So there is still a margin of progress.

Among the measures that reduce the level of risk, the priority was set on prevention, in order to reduce the probability of occurrence of the major scenarios when possible. Three main types of preventive measures were identified:

1. Developing an integrated electronic system able to detect the opening of the PV panel circuit and to short-circuit immediately the panel. This device reduces the possibility of electric shocks for people and prevents the formation of electric arcs and sparks that may inflame kerosene in case of leaks;
2. Developing a frangible support structure supporting each panel independently, in order to fold down when submitted to a given energy level;
3. Designing the large-scale PV systems as a series of modules separated by empty spaces to circulate inside the system
4. Designing PV panels incorporating a weft to ensure integrity of the panel after a shock and preventing the formation of debris.

From the results of this study, it appears that existing techniques used in large-scale PV systems are not suitable for airport areas as they increase the risks of major accidents and make them unacceptable for airport managers and aviation authorities. We encourage a restudy, which incorporates the solutions suggested in this paper to reduce the risk of major accident scenarios at the same level than without the system.

Doing such safety improvements and then reevaluating PV installations in airports could promote the development of that technology in airport areas.

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